

Photon and η Production in p+Pb and p+C Collisions at $\sqrt{s_{NN}} = 17.4$ GeV

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Measurements of direct photon production in p+Pb and p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV are presented. Upper limits on the direct photon yield as a function of p_T are derived and compared to the results for Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The production of the η meson, which is an important input to the direct photon signal extraction, has been determined in the $\eta \rightarrow 2\gamma$ channel for p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV.

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The search for a deconfined state of nuclear matter, the so-called Quark-Gluon Plasma (QGP), has been the driving force behind the program of high-energy heavy-ion research in the last decades. A variety of results from measurements at the CERN-SPS and RHIC at BNL, and most recently at the LHC at CERN strongly suggest the existence of a deconfined phase. One of the earliest pro-

posed QGP signatures, the production of thermal direct photons [1], has been exceedingly difficult to establish experimentally [2, 3].

Since photons do not interact via the strong force, they leave the interaction zone without modification, carrying information about the system at the time of their production. Direct photons, i.e. all photons not origi-

nating from decays of long-lived particles, thus allow to probe the entire history of the collision process. The direct photon yield includes a prompt contributions from initial hard scatterings of the partons, that can be described by perturbative QCD calculations. Thermal direct photons are those produced in the later equilibrated phase of the heavy-ion collision with a yield that will be characterized by the temperature of the hot and dense matter created [4]. Measurements of direct photon production in p+A or p+p collisions are a necessary baseline to determine the prompt photon contribution in A+A collisions. Aside from nuclear effects on parton distribution functions, the prompt direct photon contribution in a nucleus-nucleus collision is expected to scale with the number of binary nucleon-nucleon collisions, as has been demonstrated in recent measurements by the PHENIX experiment at RHIC [5, 6]. An accurate determination of the prompt direct photon component based on a direct photon measurement in p+p collisions at the same incident energy [5], which is in agreement with pQCD predictions, allowed to extract a possible excess contribution of direct photons in A+A collisions, that may then be attributed to a thermally equilibrated phase. The spectra of these thermal direct photons can be used to constrain the initial temperature of the medium created in the heavy-ion collision. Recent measurements of the virtual direct photon spectrum in the electron-positron channel by the PHENIX experiment have provided first evidence for a direct photon enhancement beyond the expected prompt photon yield in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [7], which may be explained by a thermal production mechanism.

The first observation of a significant direct photon signal in heavy-ion collisions was reported by the WA98 experiment [8, 9] at the SPS. The direct photon yield was measured in central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. At the time, no direct photon measurement in p+p collisions at $\sqrt{s} = 17.3$ GeV was available as a reference to determine the expected prompt photon signal. Instead, direct photon measurements in p+p and p+A collisions at the higher $\sqrt{s_{NN}}$ of 19 GeV by other experiments [10–12] were used as a reference to determine the prompt photon signal by applying x_T -scaling ($x_T = 2p_T/\sqrt{s}$) to account for the difference in the center-of-mass energies [8, 13]. However, these measurements were only available for comparisons above $p_T \sim 2$ GeV/c, and differed from each other by as much as a factor of 2. Furthermore, pQCD calculations of prompt direct photon production in the SPS energy regime were generally unable to reproduce the measurements without the introduction of intrinsic k_T contributions [14]. As a result, the prompt photon yield could not be estimated without large systematic uncertainties, and therefore reliable limits on a thermal contribution to the observed direct photon excess in central Pb+Pb collisions could not be inferred without similarly large systematic uncertainty [15, 16]. Therefore, the magnitude, and even the existence, of a possible thermal contribution to the direct

photon spectrum at SPS energies has remained an open question.

In this paper, results of a direct photon analysis of p+Pb and p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV by the WA98 experiment are presented. Upper limits on the direct photon yield are obtained and used in a comparison to the previously published WA98 results on direct photon production in central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. New measurements of the η -yield in p+C collisions are presented and combined with the WA98 measurements of the neutral pion yield to extract the η/π^0 -ratio, which is a crucial input to the determination of the direct photon yield.

In 1996 the WA98 experiment took data with a secondary beam of 160 GeV/c momentum on Pb and C targets, corresponding to a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 17.4$ GeV. The primary proton beam of 450 GeV/c from the SPS accelerator impinged upon a beryllium target and a secondary mixed beam of 160 GeV/c momentum, consisting primarily of protons and charged pions, was selected and delivered to the WA98 experiment. A clean beam trigger was defined as a signal in a plastic scintillator start counter, located 3.3 m upstream of the target, with no coincident signal in a veto scintillator counter (which had a 3 mm diameter circular hole and was located 2.7 m upstream of the target), or in beam halo scintillator counters (covering the transverse region beyond the veto counter up to a radius of 25 cm). Two threshold Čerenkov counters were used for the identification of the beam particles. Proton projectiles were selected by requiring signals below the corresponding thresholds for pions and kaons in both detectors. Only events where both Čerenkov detectors identified the beam particle as below threshold, and therefore a proton, were used in this analysis. The minimum bias trigger was determined from the total transverse energy deposited in the range $3.5 \leq \eta \leq 5.5$ as measured by the MIRAC calorimeter [17].

Two targets were used for the data presented here: A ^{208}Pb target with a thickness d_{Pb} of 0.436 mm and an areal density ρ_{Pb} of 495 mg/cm², and a ^{12}C target with $d_C = 10.022$ mm and $\rho_C = 1879$ mg/cm². A total of $1.2 \cdot 10^6$ ($1.0 \cdot 10^6$) minimum bias events were recorded for p+C (p+Pb) collisions, with a factor of ~ 30 (~ 8) more minimum bias events sampled by a high energy photon trigger described below. The measured WA98 minimum bias cross section σ_{mb} of 193 mb (1422 mb) for p+C (p+Pb) corresponds to 86% (81%) of the total inelastic cross section.

Photons were measured with the 10,080 module lead-glass electromagnetic calorimeter (LEDA) located at a distance of 21.5 m downstream of the target with roughly one quarter of full azimuthal coverage in the pseudorapidity range $2.3 \leq \eta \leq 3.0$. A Charged Particle Veto (CPV) detector was placed 1 m before LEDA to reject charged clusters. To enrich highly energetic photons in the data sample, a high energy photon (HEP) trigger derived from overlapping 4×4 groups of adjacent mod-

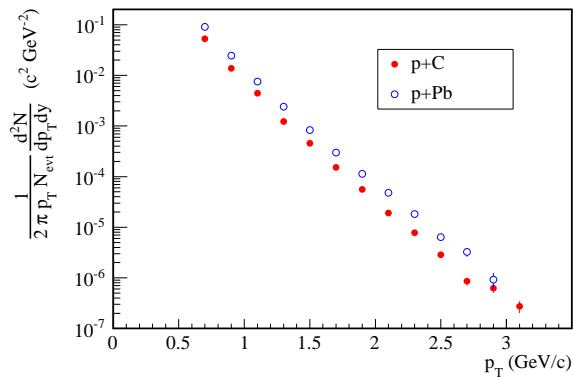


FIG. 1: Invariant inclusive photon yields from p+Pb and p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

ules (each group offset by 2 towers) in the LEDA was used. The HEP trigger reached its full efficiency for $p_T \geq 0.8$ GeV/c. With the HEP trigger, an additional $1.5 \cdot 10^6$ ($0.5 \cdot 10^6$) p+C (p+Pb) events were recorded, equivalent to an additional $3.9 \cdot 10^7$ ($8.2 \cdot 10^6$) sampled minimum bias events.

This analysis follows the procedure described in Ref. [9]. The fully corrected inclusive photon spectra measured with the electromagnetic calorimeter for both the p+Pb and p+C data sets are presented in Fig. 1. For $p_T \geq 1.2$ GeV/c the triggered data sample is used.

The spectra have been corrected for the geometrical acceptance and efficiency, analogous to previous measurements by WA98 as described in Refs. [9, 18]. The acceptance correction accounts for the limited spatial coverage of the detector for single photons. The acceptance is independent of p_T and amounts to 0.245 in the rapidity interval $2.0 < y < 3.2$. The efficiency correction has been determined from GEANT simulations in which simulated clusters have been embedded into the raw data to undergo the full reconstruction and analysis procedures that are applied to the measured data. The results have been validated with an independent Monte-Carlo simulation. The efficiency correction accounts for defective detector modules, finite energy resolution effects, and the cuts applied to the data. The absolute energy scale was fixed to the neutral pion mass as described in Ref. [18].

Off-target events were subtracted on a statistical basis by using the results obtained from data samples taken without a target in place. The CPV was used to identify photon conversions and determine the fraction of charged particles registered as photons in the LEDA. As the CPV was not available during all p+A runs, the fraction of charged particles has been determined on a statistical basis and with a limited p_T coverage. It has been extended by scaling the correction used in peripheral Pb+Pb collisions, the scaling factors have been validated with Hijing and AMPT simulations. The correction for the amount of (anti-)neutrons falsely detected

in the LEDA as photon hits was determined from simulations based on the results for peripheral Pb+Pb collisions presented in Ref. [9], using scaling factors determined from the same Hijing and AMPT simulations that were used for the CPV information. To account for the steeply falling shape of the spectra, the contents of the p_T bins are shifted along the y-axis employing a fit with a Hagedorn function $f_{Hag} = a \cdot [b/(b + p_T)]^2$ to represent the correct value at the bin center.

The systematic errors on the inclusive photon measurement are summarized in Table I for two representative p_T values. The uncertainty of the efficiency correction includes the uncertainties introduced by the cut on the shower shape in the detector, by the finite energy resolution of the detector, which is the dominant uncertainty at the highest p_T , as well as the conversion correction. The p_T dependent uncertainty for the energy scale has been determined by variation of the scale within its $\pm 1.5\%$ accuracy, estimated from the neutral pion analysis. The errors bars of Fig. 1 show the quadratically summed statistical and systematic uncertainties

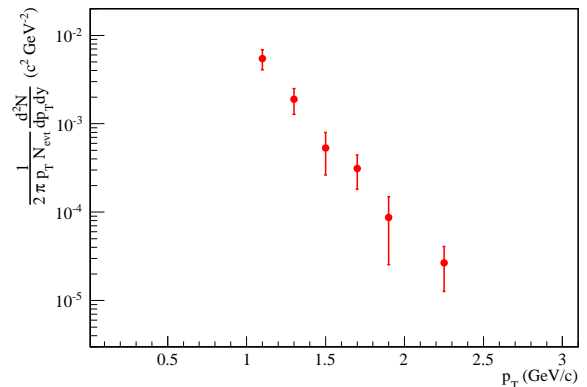


FIG. 2: Invariant η yield measured in p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV in the $\eta \rightarrow 2\gamma$ channel. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

The direct photon yield is calculated as a fraction of the inclusive photon yield presented above, following the method described in Ref. [9]. The direct photon yield for each p_T interval is calculated as:

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\text{inclusive}};$$

$$R_\gamma = \frac{(\gamma/\pi^0)_{\text{meas}}}{(\gamma/\pi^0)_{\text{decay}}}$$

In the double-ratio R_γ , systematic uncertainties that are present in the neutral pion and in the inclusive photon measurement partially cancel, thereby reducing the total systematic uncertainty on the measurement. The neutral pion yield in the $\pi^0 \rightarrow 2\gamma$ channel for the two

data sets has been presented in Ref. [18]. We use a fit to the π^0 spectra with a Hagedorn function as reference in the measured $(\gamma/\pi^0)_{\text{meas}}$ ratio to overcome the different bin widths.

To determine the $(\gamma/\pi^0)_{\text{decay}}$ ratio for the decay photons a Monte Carlo simulation was employed to calculate the photonic decays of the relevant mesons – π^0 , η , η' , ω , and K_s^0 – based on the measured neutral pion spectra in p+Pb (p+C) collisions and by employing m_T -scaling for the heavier mesons. An η/π^0 -ratio of 0.55 ± 0.08 was assumed [9], consistent with the measured result presented here.

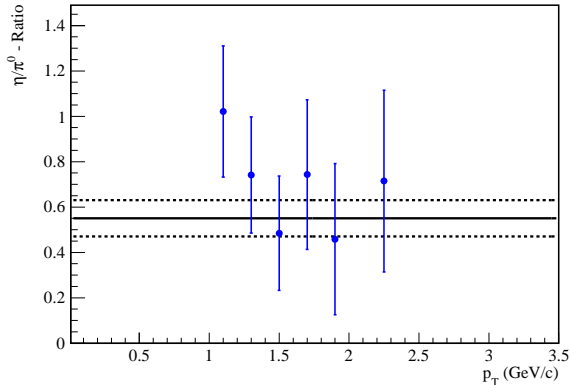


FIG. 3: The ratio of the η and π^0 yield as a function of p_T in p+C collisions at $\sqrt{s_{\text{NN}}} = 17.4$ GeV. The π^0 spectrum is taken from [18]. The error bars represent the quadratic sum of the statistical and systematic uncertainties. The ratio assumed in [9] with its respective uncertainties is indicated by the horizontal lines.

The η -production in p+Pb and p+C collisions at $\sqrt{s_{\text{NN}}} = 17.4$ GeV has been analyzed via the $\eta \rightarrow 2\gamma$ -channel by an invariant mass analysis analogous to that used for the neutral pions [18]: the two-photon invariant mass is calculated for all possible photon pair combinations in an event, and the η yield is extracted statistically from the counts in the η mass peak. A requirement that the asymmetry of the photon pairs $\alpha = \frac{E_1 - E_2}{E_1 + E_2}$, with $E_{1,2}$ being the energies of photon 1 and 2, should be less than 0.7 was applied to reduce the combinatorial background. In order to remove this background, the invariant mass distributions of uncorrelated photon pairs taken from different events with identical multiplicity were determined. These distributions were scaled to the background level in the real pair distribution for each p_T -interval and subtracted to obtain the p_T -dependent η -yield. The acceptance and efficiency corrections to the η yield were determined from the same Monte-Carlo simulations used for the inclusive photon and neutral pion analyses.

A significant η result could be obtained only for the p+C data set with the HEP trigger. The fully corrected η spectrum is shown in Fig. 2. The resulting measured η/π^0 -ratio for p+C shown in Fig. 3 is consistent with the ratio assumed in [9], shown as horizontal lines.

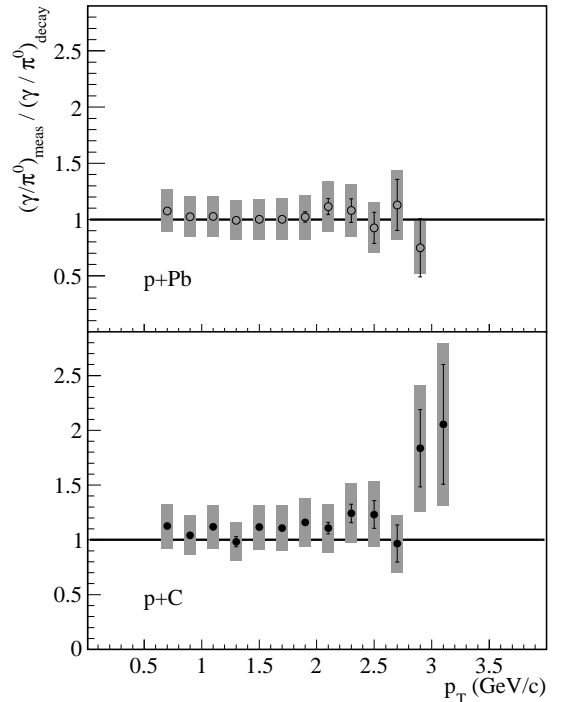


FIG. 4: Double ratio $R_\gamma = (\gamma/\pi^0)_{\text{meas}}/(\gamma/\pi^0)_{\text{decay}}$ for p+Pb (upper panel) and p+C (lower panel) collisions at $\sqrt{s_{\text{NN}}} = 17.4$ GeV. A fit to the neutral pion data from [18] has been used for the measured π^0 result. The error bars show the statistical errors and the shaded areas show the systematic uncertainties of the measurements.

The double ratios R_γ for p+Pb and p+C are shown in Fig. 4. The uncertainty of the energy scale largely cancels out in the double ratio. No significant photon excess is observed in the p_T range relevant for thermal photon production. However, it is possible to determine upper limits for the production of direct photons up to $p_T = 3.2$ GeV/c, which are shown in Fig. 5. The upper limits are extracted as 1.28σ above the measured result (using $R_\gamma = \max[1, R_\gamma^{\text{meas}}]$), as used for the previously published Pb+Pb results [8, 9, 19], and are plotted as vertical arrows with the tail indicating the upper limit.

These new results are compared to the previously published results for central Pb+Pb collisions [8, 9] in Fig. 6 after scaling the upper limits for the p+A datasets by the corresponding ratio of the number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, as determined from Glauber calculations [20] using a nucleon-nucleon inelastic interaction cross section of $\sigma_{\text{inel}}^{NN} = 31.8$ mb. The transverse energy E_T was modeled by sampling a negative binomial distribution to determine the E_T contribution of each participating nucleon. To these the same selection on E_T as used in the event selection by the WA98 trigger was applied, to determine the $\langle N_{\text{coll}} \rangle$ values. With this procedure the number of binary nucleon-nucleon collisions has been determined as $\langle N_{\text{coll}} \rangle^{p+C} = 1.7 \pm 0.2$ and

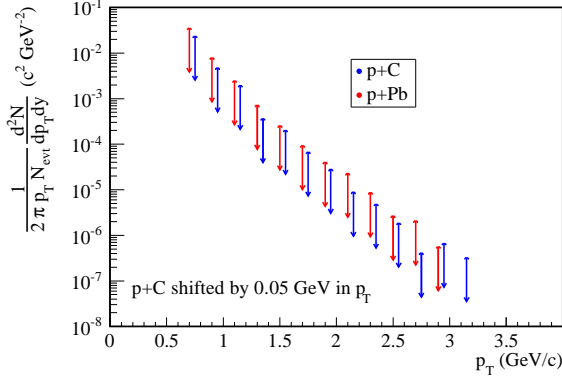


FIG. 5: Upper limits, quoted at 1.28σ , for the direct photon production in p+Pb and p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV. The p+C values have been shifted higher by 0.05 GeV/c in p_T for visibility.

	1.25 GeV/c	2.9 GeV/c
Efficiency	8.5%	21.9%
Background Correction	2.5%	2.5%
Energy Scale	13.8%	28.7%
Geometric Acceptance	2.0%	2.0%
Charged Particles	9.2%	8.0%
(Anti-)Neutrons	5.7%	2.8%
m_T -scaling	1%	1%
η/π^0 -ratio	3%	3%
Fit to π^0 -spectrum, p+Pb	2.3%	7.1%
Fit to π^0 -spectrum, p+C	2.4%	7.0%

TABLE I: Systematic uncertainties on the direct photon yield measurement at two representative p_T values.

$\langle N_{coll} \rangle^{p+Pb} = 3.8 \pm 0.4$ [18]. For the Pb+Pb data, the events were selected as the 13% most central fraction of the minimum bias cross section of $\sigma_{mb}^{Pb+Pb} \approx 6300$ mb, corresponding to $\langle N_{coll} \rangle^{Pb+Pb-cent} = 727.8 \pm 72.8$.

The direct photon yields observed for central Pb+Pb collisions, scaled by the number of nucleon-nucleon collisions, are consistent with the upper limits from both the p+Pb and p+C results, as shown in Fig. 6. Therefore, the new results do not allow to constrain the prompt photon contribution to the Pb+Pb direct photon yield, and hence do not allow to draw definitive conclusions about a possible thermal contribution to the Pb+Pb direct photon yield. A new NLO pQCD calculation is shown in both panels for p+p collisions at $\sqrt{s_{NN}} = 17.4$ GeV [21], scaled by $\langle N_{coll} \rangle^{Pb+Pb-cent}$. The calculation employs the GRV photon fragmentation function [22] and is shown for scales $\mu = 0.5p_T, p_T, 2p_T$, which reflect the theoretical uncertainties. Within these the NLO calculations are able to describe the central Pb+Pb direct photon excess, and hence do not provide evidence for a thermal direct photon contribution.

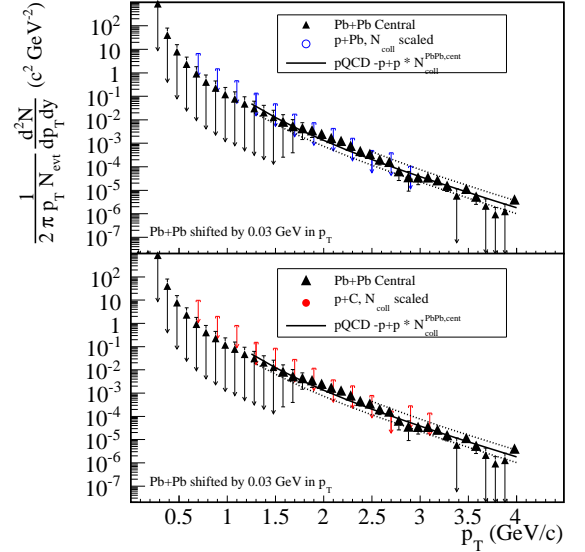


FIG. 6: Comparison of the direct photon spectra for central Pb+Pb collision from [9] to the p+Pb (upper panel) and p+C results (lower panel) presented in this paper. The two p+A data sets have been scaled by the ratio of the number of binary nucleon-nucleon collisions $N_{coll}^{PbPb}/N_{coll}^{p+A}$. NLO-pQCD calculations for p+p collisions scaled by N_{coll}^{PbPb} for three different scales are shown as lines.

In summary, new measurements of η production in p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV have been presented. The result is in agreement with previous η/π^0 -ratio results. Inclusive photons have been measured in p+Pb and p+C collisions at $\sqrt{s_{NN}} = 17.4$ GeV, and upper limits on the production of direct photons were obtained. The results cover the p_T range of $0.7 \text{ GeV} \leq p_T \leq 3.2 \text{ GeV/c}$. Comparison of these upper limits, scaled by $\langle N_{coll} \rangle$, to the results obtained by WA98 for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV does not improve the existing experimental constraints on the production of thermal direct photons at SPS energies. Similarly, new NLO pQCD calculations of the prompt photon contribution are consistent, within uncertainties, with the observed central Pb+Pb direct photon excess. Hence, it remains an open question to what extent the direct photon signal observed by WA98 for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV may be attributed to thermal radiation.

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